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North-south asymmetry in solar activity: predicting the amplitude of the next solar cycle

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ABSTRACT

Using Greenwich and SOON sunspot group data during the period $1874-2005$, we find that the sums of the areas of the sunspot groups in $0^\circ-10^\circ$ latitude-interval of the Sun's northern hemisphere and in the time-interval, minus 1.35 year to plus 2.15 year from the time of the preceding minimum–and in the same latitude interval of the southern hemisphere but plus 1.0 year to plus 1.75 year from the time of the maximum–of a sunspot cycle are well correlating with the amplitude (maximum of the smoothed monthly sunspot number) of its immediate following cycle. Using this relationship it is possible to predict the amplitude of a sunspot cycle by about $9-13$ years in advance. We predicted 74 ± 10 for the amplitude of the upcoming cycle 24. Variations in solar meridional flows during solar cycles and $9-16$ year variations in solar equatorial rotation may be responsible for the aforementioned relationship.

Key words: Sun: rotation–Sun: magnetic field–Sun: activity–Sun: sunspot cycle

1 INTRODUCTION

The prediction of the level of activity is important because solar activity impact us in many ways (Hathaway et. al. 1999; Hathaway & Wilson 2004). For example, solar flare activity cause geomagnetic storm that can cripple communication and damage power grids. There is also mounting evidence that solar activity has an influence on terrestrial climate and space weather (Rozelot 2001; Hiremath & Mandi 2004; Georgieva et al. 2005). Many attempts have been made to predict the amplitude of a new sunspot cycle by using old cycles data with a belief that solar magnetic field persists for quite sometime (Hathaway et. al. 1999). The existence of a statistically significant difference between the levels of solar activity in the northern and the southern hemispheres is shown by several statistical studies for most of the solar activity phenomena (Garcia 1990; Carbonel et al. 1993). The north-south asymmetry is unusually large during the Maunder minimum (Sokoloff 1994). The existence of a few periodicities in the north-south asymmetry of solar activity is also shown (Javaraiah & Gokhale 1997a; Knaack et al. 2005). In addition, there are considerable north-south differences in the differential rotation rates and the meridional motions of sunspots (Javaraiah & Ulrich 2006). Helioseismology measurements also show the existence of north-south differences in the solar rotational and meridional flows (Zaatri et al. 2006). Therefore, north-south asymmetry in solar activity is an important physical solar property and it greatly helps for understanding variations in the solar activity (Sokoloff 1994; Javaraiah & Gokhale 1997a; Knaack et al. 2005). In this letter we have used this property of a solar cycle to predict the amplitude of the upcoming solar cycle 24.

2 DATA ANALYSIS AND RESULTS

We have used the Greenwich sunspot group data during the period $1874-1976$, and the sunspot group data from the Solar Optical Observing Network (SOON) of the US Air Force/US National Oceanic and Atmospheric Administration during 1977 January $1-2005$ September 30. We have taken recently updated these data from the NASA website of David Hathaway (`http://solarscience.msfc.nasa.gov/greenwich.shtml`). These data include the observation time (the date and the fraction of the day), the heliographic latitude and the longitude, central meridian distance (CMD), the corrected whole spot area (in mh), etc. for each day of the spot group observation (130 mh $\approx$ 10^{22} Mx). In the present analysis we have excluded the data corresponding to the $|CMD| > 75^\circ$ in any day of the spot group life-time. This precaution considerably reduces the errors in the derived results due to the foreshortening effect. In case of SOON data, we increase area by a factor of 1.4. David Hathaway found this correction is necessary to have a combined homogeneous Greenwich and SOON data (see

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aforementioned web-site of David Hathaway.) We binned the daily data into 10° latitude intervals, in both the northern and the southern hemispheres, and determined sum of the areas (AT) of the spot groups in each 10° latitude interval, separately for the rising and the declining phases of the sunspot cycles 11 – 23. (It should be noted here that cycle 23 is not yet complete. The data are available for about 9 years of this cycle. In case of cycle 11, the data are available for the last 4 years.)

We determined cross-correlations between AT and amplitude of cycle (RM). We have taken the values of RM (which is the largest smoothed monthly mean sunspot number), and the epochs of maxima (TM) and the preceding minima (Tm) of cycles 12 – 23 from the web-site, `ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS`. Fig. 1 shows the cross-correlation function, $CCF(RM, AT)$, in different latitude intervals (*a positive value of lag indicates that RM leads AT*). In this figure it can be seen that except for AT during the declining phases of the cycles and in 0° – 10° latitudes intervals of both the northern and the southern hemispheres, for each of the remaining cases, *viz.* AT in 10° – 20° and 20° – 30° latitude intervals during the declining phases of the cycles and in all the latitude intervals during the rising phases of the cycles, the corresponding $CCF(RM, AT)$ has a weak peak at $lag \geqslant 0$. This suggests that in all these latitude intervals AT and RM variations are approximately in the same phase or RM leads AT. In case of AT during the declining phases of the cycles, in 0° – 10° latitude interval of the southern hemisphere the $CCF(RM, AT)$ has a well defined peak (value 0.76) at $lag = -1$, suggesting that AT leads that of RM by about 5 – 10 years. In the same latitude interval of the northern hemisphere the $CCF(RM, AT)$ is found to be having a broad peak with two humps (values 0.8 and 0.6) at $lag = 0$ and $lag = -2$, suggesting that AT leads RM by about 5 – 25 years. These results indicate that AT can be used to predict RM.

There exist a number of short-term periodicities, a few days to a few years, in both the solar activity and the solar rotation (Bai & Sturrock 1993; Javaraiah & Komm 1999; Knaack et al. 2005). Amplitude of such a periodicity largely varies during a solar cycle. Therefore, there is a possibility that AT in 0° – 10° latitude intervals of the northern and the southern hemispheres during some short intervals having strong correlations with RM. With this hypothesis we determined the maximal values of correlations between AT of cycle n and RM of cycle $n + 1$ in the following way, where $n = 12, ..., 22$ is the cycle number: First we determined the values of AT in the intervals which were chosen arbitrarily around the epochs of the maxima and the preceding minima of the cycles. The AT determinations are repeated by increasing or decreasing the lengths of the intervals with a step of $\geqslant 0.05$ year at a time. We find that in 0° – 10° latitude interval of the southern hemisphere, the correlation is maximum, coefficient of correlation $r = 0.97$ (from eleven data points), in the short (0.75 year) time-interval just after 1-year after the time of maximum of each of the cycles 12 – 23, $TM^* : TM + (1.0 \textit{ to } 1.75)$ (*i.e.*, close to the time of the reversal of polarities of the polar magnetic fields). We also find that in 0° – 10° latitude interval of the northern hemisphere $r = 0.95$ is maximum in the time-interval (3.5 year), $Tm^* : Tm + (-1.35 \textit{ to } 2.15)$. Both these correlations are statistically high significant with > 99.99 confidence level (from *Student's t-test*), *i.e.*, the chance of getting these relations from uncorrelated quantities is less than 0.01%. Interestingly, the existence of 0.75 year periodicity is known in solar activity (Knaack et al. 2005), and it may be a subharmonic of the well-known Rieger periodicity in solar flare activity (Bai & Sturrock 1993). The existence of 3.5 year periodicity in solar activity is also known and this periodicity seems to be more pronounced in the north-south asymmetries of solar activity and surface rotation (Javaraiah & Gokhale 1997a; Knaack et al. 2005). In Table 1 we have given the values of AT during Tm^* and TM^*. In the same table we have also given the values of the amplitudes and the epochs of maxima and minima of the sunspot cycles 12 – 23.

We find the following linear regressions fits between AT and RM correspond to the correlations above:

$$RM_{n+1} = (1.72 \pm 0.19) \times AT_n(Tm^*) + (74.0 \pm 7.0), \quad (1)$$

$$RM_{n+1} = (1.55 \pm 0.14) \times AT_n(TM^*) + (21.8 \pm 9.6), \quad (2)$$

where uncertainties in the coefficients are the formal 1-σ (standard deviation) errors from the fit. In equations (1) and (2) the slopes are on 9σ and 11σ levels, respectively. That is, they are statistically high significant. Therefore, the relationship between AT_n and RM_{n+1} is well described by these linear equations. It should be noted here that always Tm^* is associated with 0° – 10° latitude interval in the northern hemisphere, whereas TM^* is associated with 0° – 10° latitude interval of the southern hemisphere (for other combinations, *i.e.*, TM^* with 0° – 10° interval of the northern hemisphere and Tm^* with 0° – 10° interval of the southern hemisphere the values of r found to be mere 0.11 and -0.24, respectively).

Using equations (1) and (2) the amplitudes of the upcoming sunspot cycles can be predicted by about 13 years and 9 years in advance, respectively. The results of the least-square fits are shown in Fig. 2(a). Fig. 2(b) shows the correlation between the simulated amplitudes (PM) [simulated using equations (1) and (2)] and the observed amplitudes (RM) of the cycles 13 – 23. The correlations between PM and RM and their levels of significance are the same as those of AT_n and RM_{n+1}.

Using equation (1) and (2) we obtained the values 112 ± 13 and 74 ± 10, respectively, for RM of the upcoming cycle 24 (the uncertainty is 1σ value). The latter is more statistically significant than the former. Hence, by using equation (2) the amplitude of a cycle can be predicted accurately by 9 years advance. Therefore, we predict 74 ± 10 for RM of cycle 24. This is equal to the value predicted by Svalgaard et al. (2005) (see Section 3). The pattern of the mean cycle-to-cycle variation of the simulated amplitudes (PM) obtained using equations (1) and (2) is found to be slightly more strikingly resemble with that of RM ($r = 0.97$). From this we get 93±10 for RM of cycle 24. However, the difference between the values obtained from equations (1) and (2) for cycle 24 is significantly large. The mean deviation is at 2σ level. Hence, we do not suggest the mean value for RM of cycle 24. Moreover, from equations (1) and (2) we can get $RM_{n+1} \approx 2.1 \times AT_n(TM^*) - 0.6 \times AT_n(Tm^*)$. [This may be a more appropriate representation, because this is included both terms, $A_n(Tm^*)$ and $AT_n(TM^*)$.]

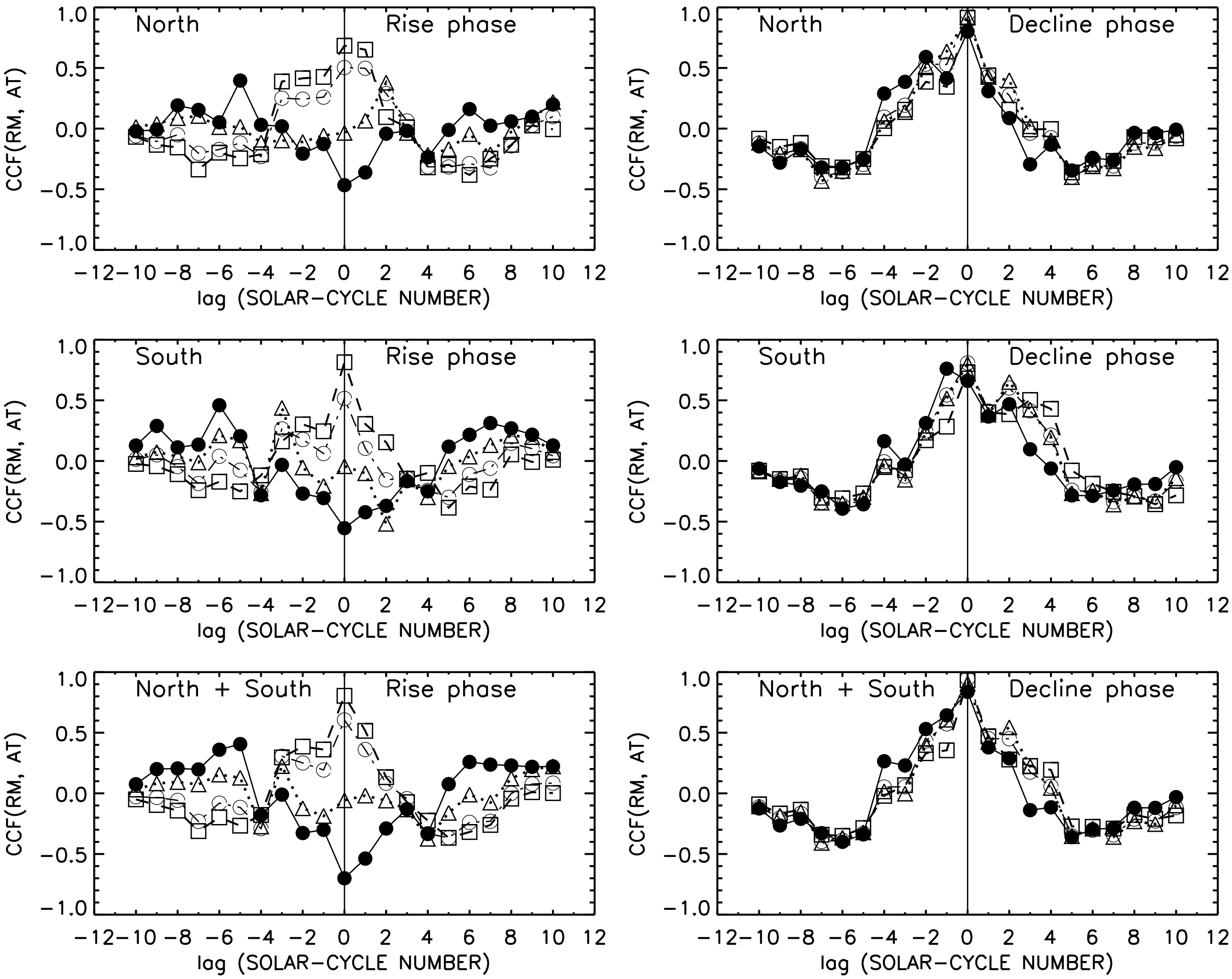

Figure 1. Plots of the $CCF(RM, AT)$ verses lag during the rising and declining phases of solar cycles 12 − 13. A positive value of lag indicates that RM leads AT. The *filled circle-solid curve, triangle-dotted curve, square-dashed curve , and open circle-dash-dotted curve* represent $CCF(RM, AT)$ in latitude intervals $0° - 10°$, $10° - 20°$, $20° - 30°$ and in whole disk, respectively.

Table 1. The maximum (RM) and the minimum (Rm) amplitudes (the largest and the smallest smoothed monthly mean sunspot numbers) of the solar-cycles 12 − 23 and the sum of the areas of spot groups (AT, normalized by 1000) in the intervals $Tm^* = Tm + (-1.35\ to\ 2.15)$ and $TM^* = TM + (1.0\ to\ 1.75)$, where TM and Tm represent the maximum and the preceding minimum epochs of the solar cycles, respectively.

Cycle	Minimum		Maximum		Latitude Int.: $0° - 10°$ (north)		Latitude Int.: $0° - 10°$ (south)	
n	Tm	Rm	TM	RM	Tm^*	AT	TM^*	AT
12	1878.9	2.2	1883.9	74.6	1877.55 − 1881.05	9.47	1884.90 − 1885.65	42.11
13	1889.6	5.0	1894.1	87.9	1888.25 − 1891.75	3.22	1895.10 − 1895.85	32.64
14	1901.7	2.6	1907.0	64.2	1900.35 − 1903.85	12.98	1908.00 − 1908.75	54.64
15	1913.6	1.5	1917.6	105.4	1912.25 − 1915.75	3.74	1918.60 − 1919.35	34.58
16	1923.6	5.6	1928.4	78.1	1922.25 − 1925.75	33.96	1929.40 − 1930.15	75.96
17	1933.8	3.4	1937.4	119.2	1932.45 − 1935.95	29.96	1938.40 − 1939.15	82.01
18	1944.2	7.7	1947.5	151.8	1942.85 − 1946.35	69.35	1948.50 − 1949.25	119.65
19	1954.3	3.4	1957.9	201.3	1952.95 − 1956.45	15.23	1958.90 − 1959.65	53.01
20	1964.9	9.6	1968.9	110.6	1963.55 − 1967.05	50.31	1969.90 − 1970.65	78.28
21	1976.5	12.2	1979.9	164.5	1975.15 − 1978.65	60.05	1980.90 − 1981.65	83.53
22	1986.8	12.3	1989.6	158.5	1985.45 − 1988.95	29.85	1990.60 − 1991.35	67.48
23[a]	1996.4	8.0	2000.3	120.8	1995.05 − 1998.55	21.99	2001.30 − 2002.05	33.58

[a] indicates the incompleteness of the current cycle 23.

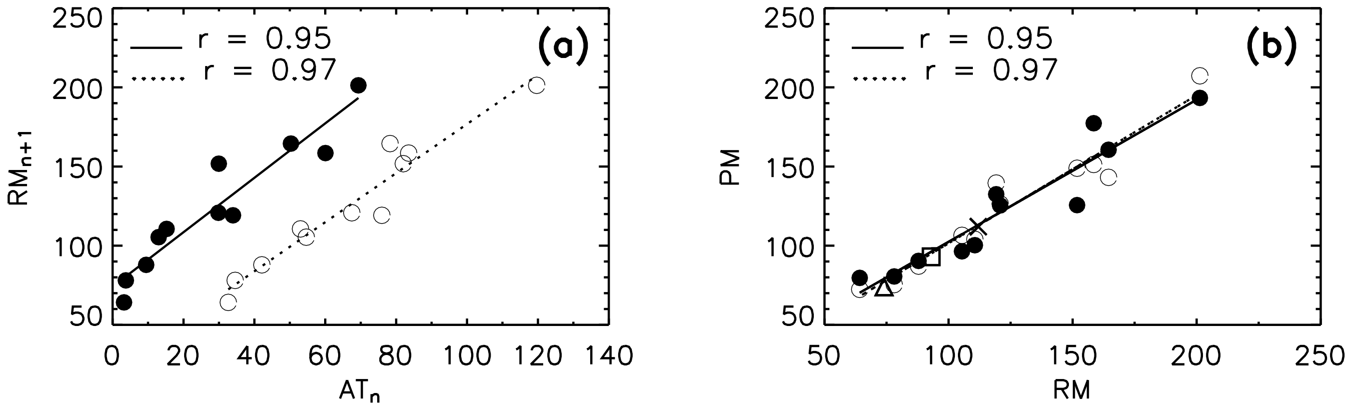

Figure 2. Plots of the correlations (a) between the *AT* (for the values given in Table 1) during the intervals Tm^* and TM^* correspond to cycle n and RM of the cycle $n+1$, and (b) between RM and the simulated amplitude PM of cycle $n+1$, where $n = 12, ..., 22$, is the cycle number. The straight lines represent the corresponding linear relationships. The values of the correlation coefficient (r) are also given. The *filled circle* and the *solid line* correspond to the AT during Tm^* and the *open circle* and *dotted line* correspond to the AT during TM^*. The *cross* and *triangle* represent the values for RM of cycle 24 obtained using AT during Tm^* and TM^*, respectively, and the *square* represents the corresponding mean value. We predict the value represented by the *triangle* for RM of cycle 24.

From this relation we get a much smaller value, 57 ± 13, for the amplitude of cycle 24 ($r = 0.95$). It is somewhat closer to the value obtained from equation (2). [The negative sign of the coefficient of $AT_n(Tm^*)$ in the aforementioned relation can be attributed to the opposite polarities of the magnetic fields at Tm^* and TM_{n+1} (in sunspot latitude belt).]

Each of the above derived values for the amplitude of the upcoming cycle 24 is less than the RM of cycle 23. This is consistent with the indication that the level of activity is now at the declining phase of the current Gleissberg cycle (Javaraiah et al. 2005). From equations (1) and (2) we can also get $AT_n(TM^*) \approx 1.11 \times AT_n(Tm^*)+33.6$. [$r = 0.94$, between the simulated and the observed $AT(TM^*)$. Note: the residual is quite large in case of cycle 23.] Hence, the magnetic field at Tm^* may contribute to the field at TM_{n+1} both directly and through influencing the field at TM^*. There is also a suggestion that when $AT_n(Tm^*)$ is zero the $AT_n(TM^*)$ is not always zero. This might have happened during the late Maunder minimum, when sunspot activity is somewhat more pronounced in the southern hemisphere than in the northern hemisphere (see Sokoloff 1994). [The current cycle 23 will be ending soon. So, using equation (1), or using the aforementioned relationship between $AT_n(Tm^*)$ and $AT_n(TM^*)$ and equation (2), an approximate prediction can be made for the amplitude of cycle 25 in a 3 years time.]

3 DISCUSSION

The strength of the preceding minimum is used to predict the strength of the maximum of the same cycle. However, it seems this methods works better after 1 – 2 year after the start of the cycle, *i.e.*, an accurate prediction is possible only by about 3 – 4 years advance. The same is also true for the predictions based on geomagnetic indices as precursor indicators (Hathaway et. al. 1999).

The magnetic fields at the Sun's polar regions are important ingredient for a dynamo model (Ulrich & Boyden 2005). The polar field is maximum near sunspot minimum. Scatten et al. (1978) have used, for the first time, the strength of the polar fields at the preceding minimum of a cycle as a precursor indicator to the strength of the following maximum. Recently, Svalgaard et al. (2005) analyzed the polar fields data during the recent four solar cycles and predicted a small amplitude, 75 ± 8, for the upcoming cycle 24. Obviously from this method the prediction can be made only by about 5 years in advance. This method seems to be more uncertain and could fail if used too early before the start of the cycle (Svalgaard et al. 2005).

Dikpati et al. (2006), by simulating the surface magnetic flux using the guidelines of a dynamo model, predicted a large amplitude, 150 – 180, for cycle 24, *i.e.*, a contradiction to the aforementioned prediction by Svalgaard et al. (2005). This discrepancy implies that the dynamo processes are not yet fully understood, making prediction more difficult (Tobias et al. 2006).

Using the well known Gnevyshev-Ohl rule or G-O rule (Gnevyshev & Ohl 1948) it is possible to predict only the amplitude of an odd numbered cycle (Wilson 1988). This is also not always possible because occasionally (for example, recently by the cycles' pair 22,23) the G-O rule is violated. A major advantage of the $AT_n - RM_{n+1}$ relationships above is that using these the amplitudes of both odd and even numbered cycles can be predicted. In addition, this new method seems to have a solid physical basis. Interestingly, the TM^* is very close to the epoch when the polar-fields polarities reversals take place (Makarov et al. 2003) and Tm^* is close to the epoch when the magnetic fields polarities reversals take place close to the equator, *i.e.*, at the beginning of a cycle and continuing through the years of minimum (Makarov et al. 2001). This suggest that the $AT_n - RM_{n+1}$ relationships are related to the 22-year solar magnetic cycle. It should be noted here that although sunspot activity is confined to middle and low latitudes, it may be caused by the global modes of solar magnetic cycle (Gokhale et al. 1992; Juckett 2003).

Reconnection of the magnetic fields of opposite polarities is believed to be the basic mechanism of flare activity. During Tm^* the magnetic field structure seem to be largely quadrupole nature, which is probably favorable for X-class flares production (Garcia 1990). The solar meridional flows transport angular momentum and magnetic field from pole to equator and vise-versa, in the convection zone. The motions of spot groups mimic the motions in the convection zone (Javaraiah & Gokhale 1997b; Javaraiah & Komm 1999). The mean meridional motion of sunspot groups is changing from pole-ward to equator-ward rapidly in $0^\circ - 10^\circ$ latitude interval of the northern hemisphere and gradually in the same latitude interval of southern hemisphere during Tm^* and TM^*, respectively (see Fig. 2 in Javaraiah & Ulrich 2006). These results indicate a participation of the meridional flows in the magnetic reconnection process and the reversals of the polarities of magnetic fields during Tm^* and TM^*. The interceptions of the pole-ward and the equator-ward meridional flows may be responsible for the quadrupole nature of magnetic fields during Tm^*. It seems that during rising phases of the cycles the flare activity is strong in the northern hemisphere and weak in the southern hemisphere, and this is opposite during the declining phases of the cycles (Garcia 1990). During the rising phases of the cycles the mean meridional velocity of spot groups is equator-ward in the northern hemisphere and pole-ward in the southern hemisphere. During the declining phases of the cycles the velocity is pole-ward in both hemispheres, but the variation is steep in the southern hemisphere, mainly in $20^\circ - 30^\circ$ latitude interval (Javaraiah & Ulrich 2006). In view of the above inferences, the north-south asymmetry in solar flare activity may be related to the north-south asymmetry in the meridional flows. The corresponding losses in the magnetic flux in the northern and the southern hemispheres caused by the reconnection processes may have a contribution for the north-south asymmetries in solar magnetic field and in sunspot-activity.

The lengths of the intervals from the beginnings of Tm^* and TM^* of a preceding cycle to TM of its following cycle vary $14 - 19$ years and $7 - 11$ years, respectively. The corresponding mean values are found to be 16 years and 9.6 years, respectively. Similar periodicities exist in both the equatorial rotation rate and the latitude gradient term of the solar rotation determined from the sunspot group data (Javaraiah & Gokhale 1997a; Javaraiah 2005; Georgieva et al. 2005). Therefore, variations in the solar meridional flows during solar cycles and $9 - 16$ year variations in the solar equatorial rotation may be responsible for the $AT_n - RM_{n+1}$ relationships above.

4 CONCLUSIONS

Using Greenwich and SOON sunspot group data during the period 1874 – 2005 we find that:

(i) The sum of the areas (AT) of the spot groups in $0^\circ - 10^\circ$ latitude interval of the Sun's northern hemisphere during the interval $Tm^* : Tm + (-1.35\ to\ 2.15)$ in a cycle is well correlated with the amplitude (RM) of its following cycle, where Tm is the time (in years) of the preceding minimum of the preceding cycle,

(ii) The AT of the spot groups in $0^\circ - 10^\circ$ latitude interval of the southern hemisphere during the interval $TM^* : TM + (1.0\ to\ 1.75)$ in a cycle is also well correlated with RM of its following cycle, where TM is the time (in years) of the maximum of the preceding cycle.

(iii) Using '(i)' and '(ii)' it is possible to predict RM of a cycle by about 13 years and 9 years advance, respectively.

(iv) We predicted 74 ± 10 for RM of cycle 24.

(v) Variations in solar meridional flows during solar cycles and $9 - 16$ year variations in solar equatorial rotation may be responsible for the relations '(i)' and '(ii)'.

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